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SEISMIC DESIGN OF A SUPER FRAME STRUCTURAL SYSTEM WITH PASSIVE ENERGY DISSIPATION DEVICES

Yukihiro OMIKA[1], Tadashi SUGANO[2], Jun OHKAWA[3], Toshiyuki YOSHIMATSU[4], Yukimasa YAMAMOTO[5] And Yasukazu TSUJI[6]

SUMMARY

A super frame structural system with passive energy dissipation devices (Super-RC frame system) has been developed and applied to a high-rise residential tower. The proposed system is composed of core walls, hat beams incorporated into the top level, outer columns and viscous dampers vertically installed between the tips of the hat beams and the outer columns. During an earthquake, the hat beams and outer columns act as outriggers and reduce the overturning moment in the core, and the installed dampers also reduce the moment and the lateral deflection of the structure. This innovative system can eliminate inner beams and inner columns on each floor, and thereby provide buildings with column-free floor space even in highly seismic regions. A 29-story reinforced concrete building incorporating this system has been designed and its structural safety has been verified.

INTRODUCTION

In Japan, since the first high-rise RC building developed by our group in the 1970’s [Muto et al, 1973] was built, a large number of high-rise RC buildings of up to 30 stories have been constructed. Furthermore, during this decade, continual research and study on high-rise RC construction engineering by our group has realized the construction of a RC residential tower with high strength materials as high as 50 stories that has same beam and column cross sections as normally designed for a 30-story high-rise concrete frame [Sugano et al, 1998]. Because of their high ductility and high degree of redundancy during inelastic behavior under earthquake excitations, the structural system used in these high-rise RC buildings has usually comprised a moment resisting frame made of high strength materials.

In recent years, because of the need for flexibility in architectural design, lateral load resisting elements have been concentrated around service cores, elevator shafts and stairwells to create column-free floor space. For high-rise residential buildings, concrete core walls around these shafts are used for shear walls against lateral forces. However, because these structural elements are often relatively small, deformation of the upper stories is liable to be high under seismic load because of the lack of lateral stiffness.

Furthermore, reduction of vibrations in structures has become an important issue, and many mechanical devices and artificial systems have been developed for seismic and/or wind response control [kobori, 1996]. As a typical example, a high-damping device (hidam) has been developed and used for passive vibration control [niwa et al, 1995]. An innovative structural system (super-rc frame system) has also been developed by utilizing the energy dissipation properties of these devices along with the core wall to reduce vibrations. This system can compensate for the lack of lateral stiffness of the core wall at the upper stories and thus provide a column-free floor in buildings even in highly seismic regions.

This paper first reports the concept of the developed structural system and the fundamental characteristics of the dynamic response, and then presents its practical implementation in a 29-story residential building, now under construction in tokyo.

[1] *Architectural and Engineering Design Group, KAJIMA CORPORATION, Tokyo, Japan, E-mail omika@ae.kajima.co.jp*
[2] *Architectural and Engineering Design Group, KAJIMA CORPORATION, Tokyo, Japan,Tel +81-3-5561-2111*
[3] *Architectural and Engineering Design Group, KAJIMA CORPORATION, Tokyo, Japan,Tel +81-3-5561-2111*
[4] *Architectural and Engineering Design Group, KAJIMA CORPORATION, Tokyo, Japan,Tel +81-3-5561-2111*
[5] *Architectural and Engineering Design Group, KAJIMA CORPORATION, Tokyo, Japan,Tel +81-3-5561-2111*
[6] *Architectural and Engineering Design Group, KAJIMA CORPORATION, Tokyo, Japan,Tel +81-3-5561-2111*

2. CONCEPT OF STRUCTURAL SYSTEM

The developed structural system consists of a T-shaped super structure composed of a core wall and hat beams, outer columns, flat slabs and viscous dampers. The concept of the structural system is shown in Figure1.

A reinforced concrete core wall usually located in the center of the floor and made of high-strength materials, can resist most lateral external loads. To avoid the interference with occupiable space, the hat beams are only located at the top of the structure. The outer columns are arranged round the exterior and mainly support vertical loads. They sometimes compose a perimeter frame with shallow spandrel beams, but have less lateral resistance than the core wall. The viscous dampers are installed vertically between the tips of the hat beams and some of the outer columns. They comprise extensively developed high-performance oil dampers (HiDAM). When lateral loads act on the structure, bending deformation of the core wall causes vertical deformation of the tips of the hat beams, causing them to operate the dampers and thus dissipate vibration energy during earthquake excitations. The hat beams, outer columns and viscous dampers act as outriggers protruding from the core wall. This reduces the bending moment in the core wall and the lateral deflection of the structure, specially at the upper levels. To improve the efficiency of the dampers during earthquakes, the hat beams and outer columns may be post-tensioned using high strength steel strands formed into tendons.

The floor system adopts concrete post-tensioned flat slabs in consideration of serviceability issues such as perceptibility of occupant-induced floor vibration. With this system, there are no floor beams between the core wall and the outer columns, thus inherently allowing the free passage of the building-services ductwork and piping. Moreover, story height can be reduced, leading to significant economies.

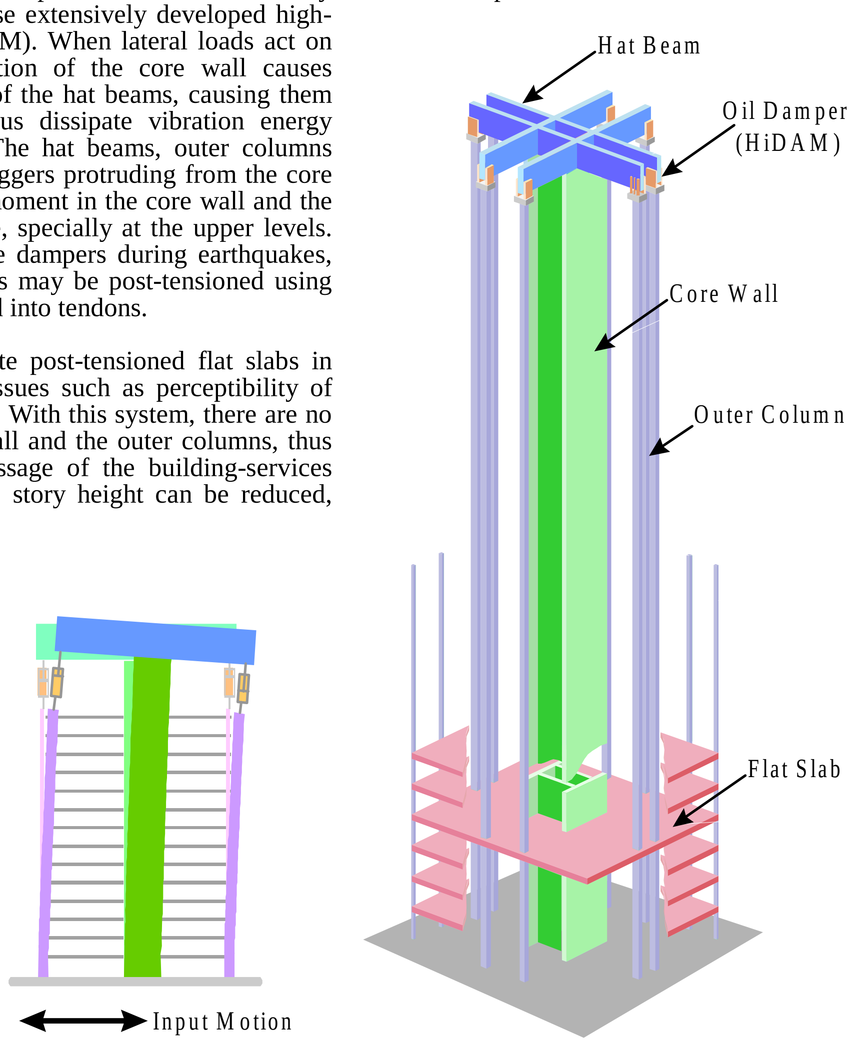


Figure 1 Concept of super frame structural system (Super-RC frame system)

3. FUNDAMENTAL CHRACTERISTICS AGAINST EARTHQUAKES

To grasp the dynamic characteristics, an earthquake response analysis using a representative model is conducted for comparison with other structural systems. The representative model is a 122m-tall 35-story residential tower with a H-shaped core wall located at the center of the floor and 16 outer columns. The structural system with this configuration employed for comparative analysis is shown in Table 1. This developed Super-RC frame system is denoted as case 1. Case 2 is a core wall system, in which core wall can only resist lateral loads. Case 3 is a core and outrigger system in which hat beams and outer columns are rigidly connected. Case 4 is a core and boundary beam system in which boundary beams are installed at each floor between a core wall and outer columns. Case 5 is a core and tubular system in which perimeter beams are rigidly connected to outer columns that can compose tubular frames. In each case, the members are rationally designed as a reinforced concrete element. Dynamic response analysis is conducted in consideration of the nonlinear characteristics of each element under destructive earthquake motion, which is simulated from the design spectrum proposed in a Japanese national project, called the “New-RC” project [AIJ, 1993].
Typical maximum responses resulting from the response analyses are shown in Figure 2. The story drift angles

remain at around 1/100, except for case 2. The core wall system cannot suppress the flexure of the upper stories by itself. Case 1, the developed system, shows the least responses of all cases. Generally, story shear force decreases with increasing natural period due to decreasing input vibration energy, but lateral deflection and story drift are liable to increase. In the developed system with the longest natural period shown in Table1, the installed viscous dampers consume vibration energy and suppress deformation, while maintaining the benefits of the reduction of induced vibration energy.

Table 1 Comparative study on structural system

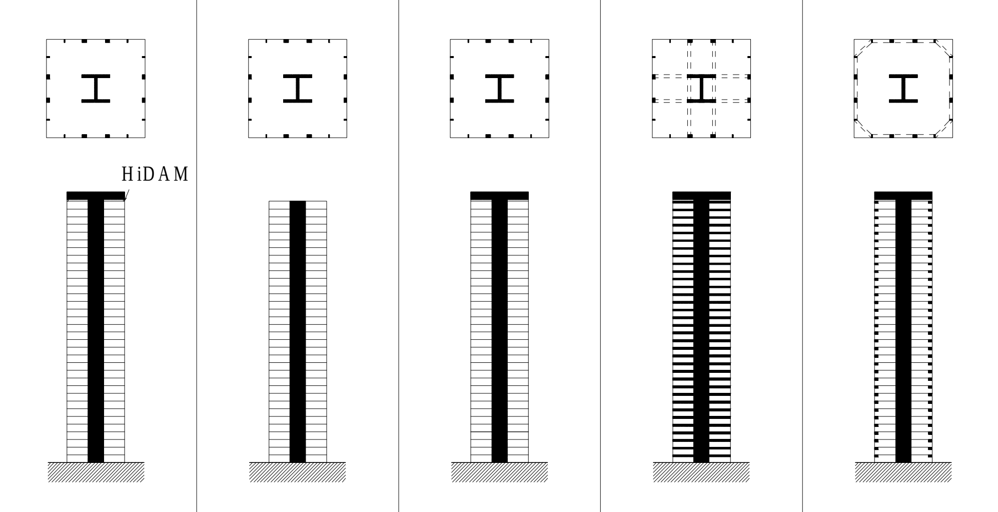
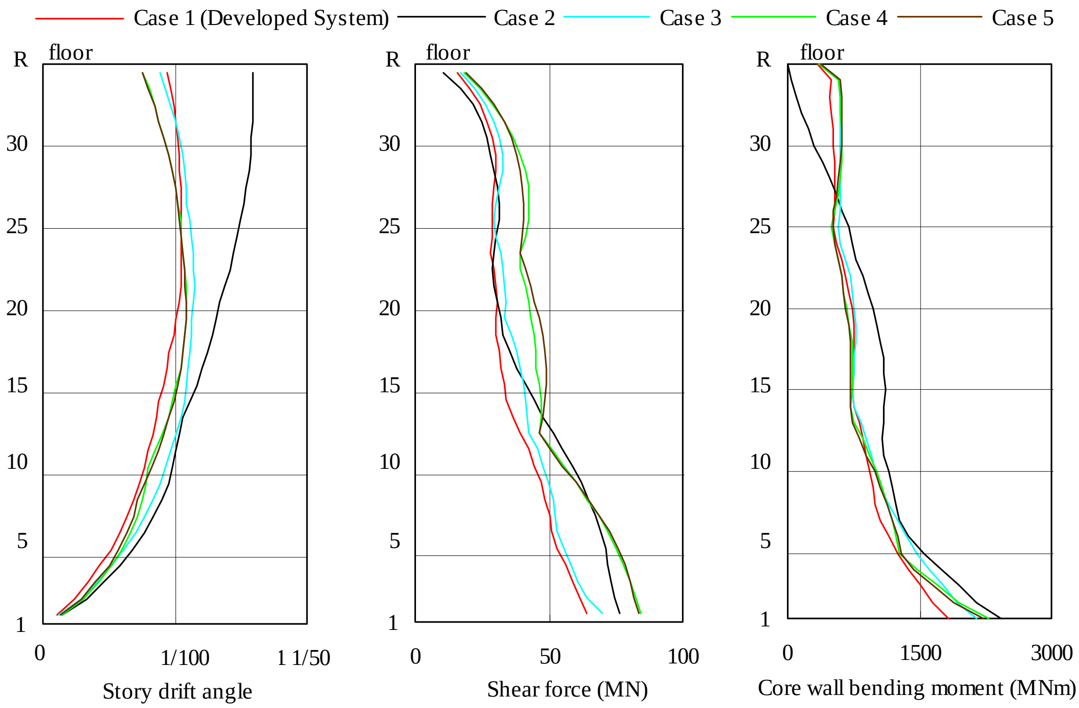
Case 1	Case 2	Case 3	Case 4	Case 5
Super-RC Frame	Core Wall	Core Wall with Hat Beam	Core Wall and Boundary Beam	Core Wall and Tubular Frame
				
T_1=3.53 sec	T_1=3.31 sec	T_1=3.26 sec	T_1=2.98 sec	T_1=2.77 sec

Figure 2 Maximum responses in comparative study



4. APPLICATION TO RESIDENTIAL TOWER

4.1 OUTLINE OF BUILDING AND STRUCTURAL PLANNING

Shiba Park-Tower, a 29-story residential tower, is located in Minato-ku, Tokyo. It is rectangular in plan, measuring 32.5 by 36.0m. It has a gross area of about 32,300m^2 and is about 90m high, as shown in Figure 3. It has 25 stories above ground used as a condominium with story heights of 3.2 to 5.0m, and 3 stories below ground used primarily as a parking garage and machine rooms.

The design project started in 1997, and after several trial designs, the Super-RC frame system was adopted because of its flexibility of architectural planning. Figure 4 shows a typical floor plan, in which four L-shaped core walls around elevator shafts and stairwells are connected by four coupling beams. Outer columns and 600mm-deep shallow perimeter beams compose perimeter frames with wide openings. Hat beams 3.5m deep span between the core walls and outer columns, as seen in Figure 5. Oil dampers are installed at the tip of each hat beam (see Figure 6), with a damping coefficient of C=4.9kNs/mm. Flat slabs 300 to 400mm thick are post-tensioned using bonded and unbonded tendons.

In this building, coupling beams and oil dampers operate together to reduce the vibration of the structure under earthquake excitation. The former suppress excessive deformations in the lower levels and the latter suppress those in the upper levels.

Belled-bottom cast-in-place RC piles supported by a GL-22m hard clay layer are arranged below the core walls and outer columns as shown in Figure 5. Footing beams 6.5m deep have the ability to resist the overturning moment at the base of the core walls and no uplift of the footings occurs even in destructive earthquakes.

Figure 3 Shiba Park-Tower

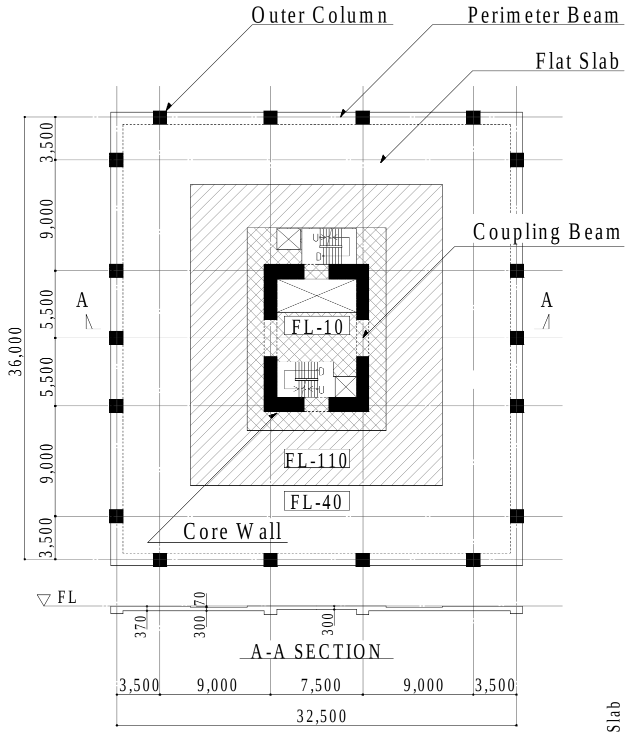


Figure 4 Typical floor plan

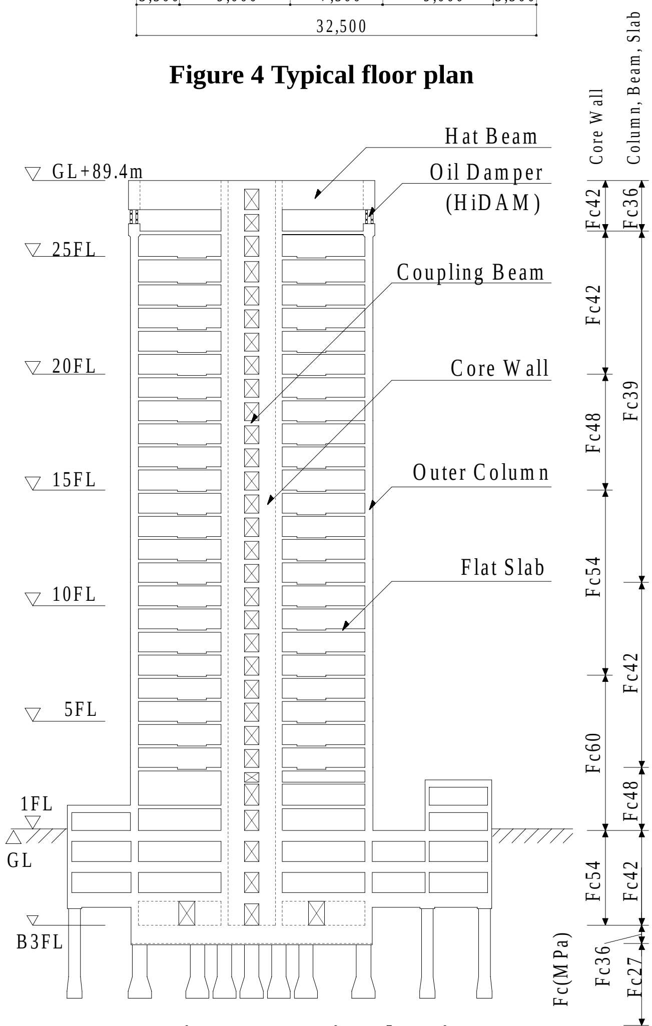


Figure 5 Framing elevation

4.2 DESIGN PHILOSOPHY AND CRITERIA

The aseismic design criteria for this building are described in Table 2. Two design procedures, static and dynamic, are carried out, and the satisfaction of these criteria assures the building's safety. Perimeter frames are designed using so-called strong-column-weak-beam concept. Core walls and hat beams are prevented from yielding except for the base of each core wall, and coupling beams are required to possess sufficient ductility to prevent excessive deformation of the structure. In other words, some surplus strength is contained in the bearing force of the core walls and so forth. For example, for the ultimate bending strength of the core walls, more than 1.5 times the stress is provided at Stage 2 for the base and at Stage 3 for the rest. The performance criteria of the dampers are a maximum damping force of 1373kN and a stroke of ±150mm.

Table 2 Aseismic design criteria

Design Procedure	Limit State or Load Level	Design or Criteria
Static Design	Stage 1 : Serviceability Limit State	Temporary Allowable Stress Design
	Stage 2 : Design Limit State	Ultimate Stress Design
	Stage 3 : Ultimate Limit State	
Dynamic Design	Level 1 : Severe Earthquake	Story Drift Angle is less than 1/200 Stress of Element is less than Allowable Stress
	Level 2 : Worst Earthquake	Story Drift Angle is less than 1/100

Typical sections of the members derived from the above design philosophy are shown in Figure 6. The design strengths of the concrete shown in Figure 5 are classified according to the elements. Relatively high-strength concrete is adopted for the core wall, to ensure high stiffness and bearing force. Longitudinal reinforcing bars

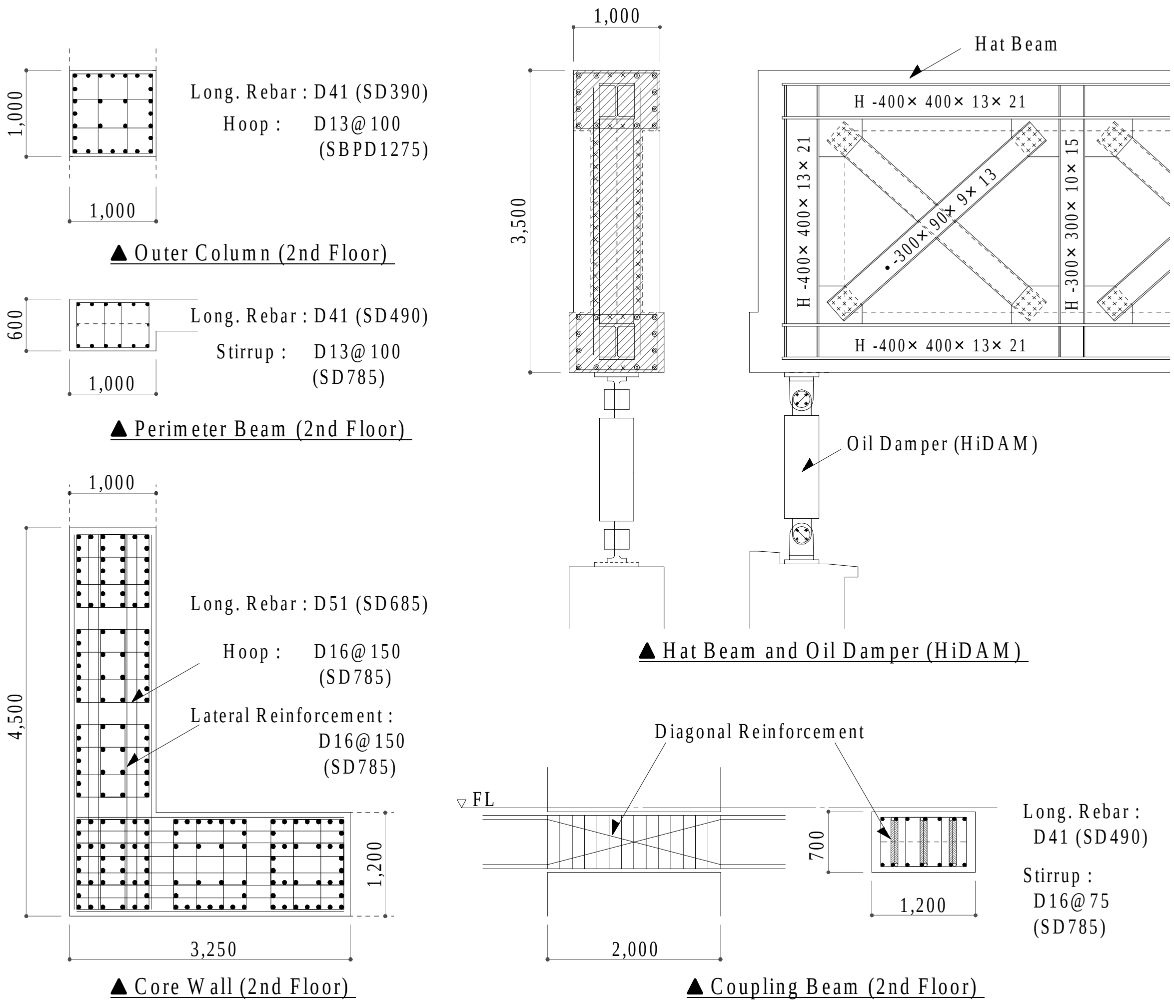


Figure 6 Typical sections of designed members

with a nominal yielding strength up to 685MPa and shear reinforcing bars up to 1275Mpa are used to improve structural ductility. Flat slabs are designed as partially post-tensioned cast-in-place concrete, and around the core walls and outer columns, slab stirrups are arranged to prevent punching shear failure.

Figure 7 shows a typical tendon arrangement of the post-tensioned slabs. It can be seen that 21.8mm-diameter tendons are arranged in some rows to allow vertical large penetrations, such as piping, mechanical ductwork, and so on. The change of penetrations is also easy during future renovations. Bonded tendons are arranged around the core walls to ensure the strength of the slabs under induced rotational displacement by the core walls during earthquakes.

The fixed anchorages of the tendons are placed on the outside of the perimeter beams and the stressing anchorages are placed in pockets on the top of the slab. Thus stressing procedure of the tendons can be usually performed on the cast-in-place concrete slab.

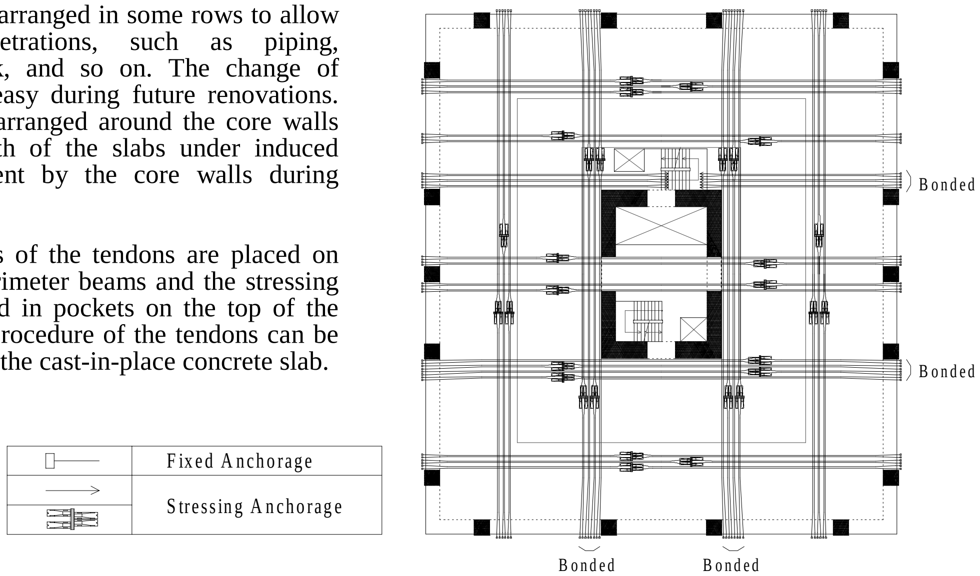


Figure 7 Typical tendon arrangement

4.3 NONLINEAR EARTHQUAKE RESPONSE OF DESIGNED SUPER FRAME STRUCTURE

In the dynamic design of the structure, nonlinear earthquake response analysis was conducted using an equivalent vibration model considering soil-structure interaction. As the entire mass of each story is concentrated at each floor level, a 26-lumped-mass model is adopted for the above ground part. The basement is assumed to be a unitary rigid body. All core walls, hat beams, outer columns, coupling beams, flat slabs and perimeter frames are modeled by equivalent bending shear elements, and horizontal and rotational interaction springs are inserted. Their nonlinear characteristics are evaluated on the basis of experimental data and their analytical study, such as a nonlinear static analysis with a fiber flexibility model for the core walls, a nonlinear FEM analysis for the flat slabs, a nonlinear static incremental loading analysis for the perimeter frames, and so on. Three recorded seismic motions, El Centro (1940 NS), Taft (1952 EW) and Tokyo101 (1956 NS), are used for the design earthquakes, with the maximum input velocity normalized at 25 cm/s (Level 1) and 50 cm/s (Level 2). An artificial earthquake is also adopted, considering seismic activities and ground conditions at the site. The damping matrix is assumed to take a Rayleigh type damping form, and the modal damping factor is estimated to be 3% for the first and second natural modes.

Figure 8 shows the resulting maximum responses in the longitudinal direction under Level 2 design earthquakes. The fundamental period for longitudinal vibration is 1.92 sec. From Figure 8, the maximum story drift angle falls within the criterion 1/100 mentioned above, and the maximum story shear is about 75MN. Without the dampers, the story drift angle might reach or exceed the criterion in the levels above the 20th floor. The ultimate bending and shearing strength of the core wall is 2 to 3 times more than the maximum response, so sufficient safety is ensured against failure.

The maximum responses of the oil dampers are summarized in Table 3, and it can be seen that all the responses fall within the described criteria.

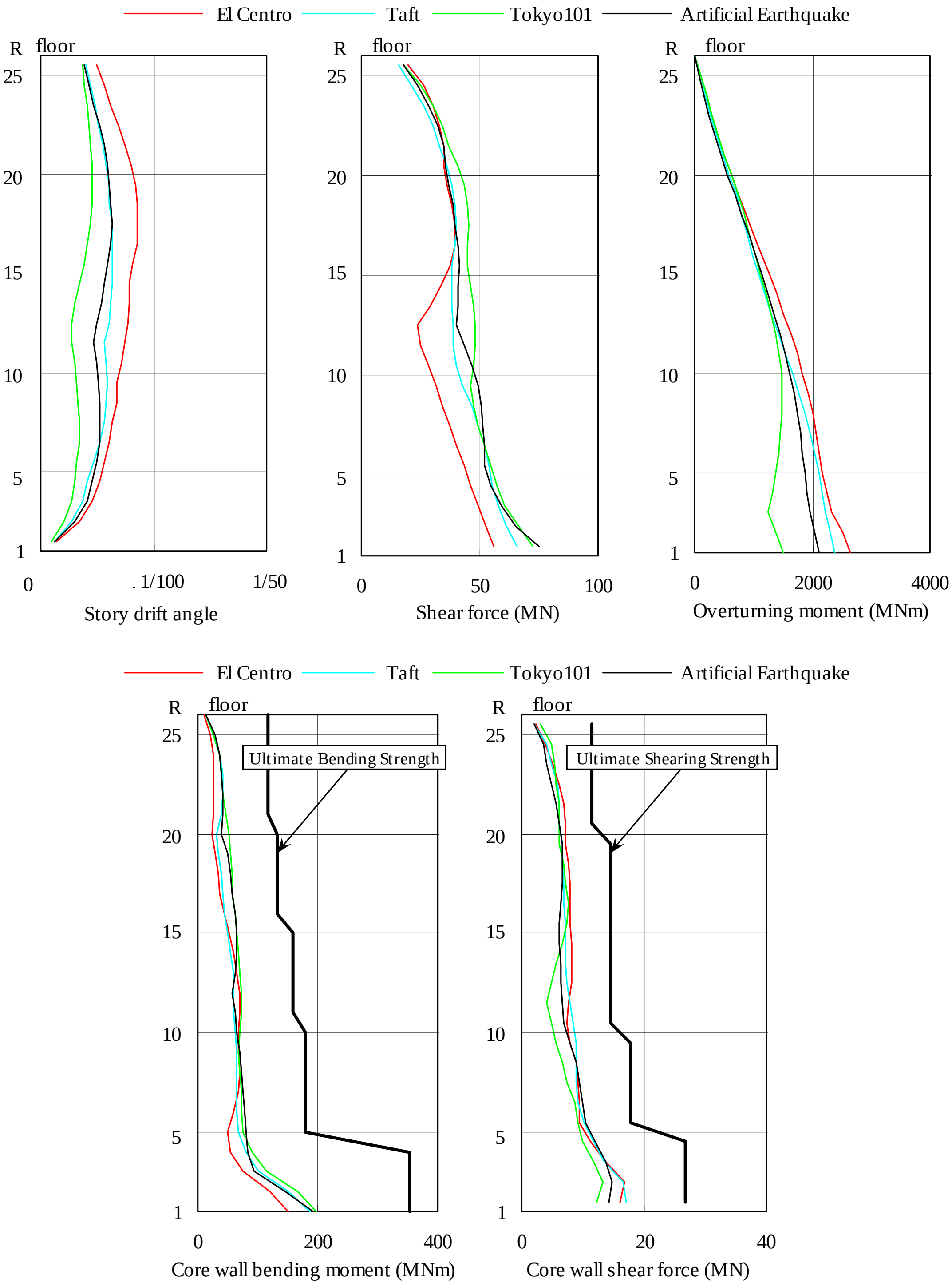


Figure 8 Typical response quantities in design analysis

Table 3 Maximum damper responses

Damper Performance	Responses	(Input wave)
Maximum Stroke	43.5 mm	(El Centro NS)
Maximum Damping Force	1022 kN	(Tokyo101 NS)

5. CONCLUSION

This paper has presented the concept and practical implementation of a newly developed structural system, a super frame structural system with passive energy dissipation devices (Super-RC frame system), which can provide column-free floor space and lead to increased flexibility in architectural design even in highly seismic regions. The results of this study and development can be summarized as follows:

1. Super frame structural system is mainly composed of core walls, hat beams, outer columns, viscous dampers and flat slabs. The high-performance oil dampers (HiDAM) play an important role in reducing vibrations under earthquake excitation.
2. The fundamental characteristics of the developed system are clarified by earthquake response analysis and compared with other structural systems.
3. The developed system is applied to a 29-story residential tower, and sufficient surplus safety is confirmed through a static and dynamic design procedure.

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REFERRENCES

AIJ (1993), *Earthquake Motion and Ground Condition*, The Architectural Institute of Japan(AIJ)

Kobori, T. (1996), “Structural Control for Large Earthquakes”, *Proceedings of the XIXth International Congress of Theoretical and Applied Mechanics*, Kyoto, Japan, 25-31 August, pp.2-28.

Muto, K. et al. (1973), “Earthquake Design of a 20 Story Reinforced Concrete Building”, *Proceedings of 5th WCEE*, June, Vol.2, pp.1960-1969.

Niwa, N. et al. (1995), “Passive Seismic Response Controlled High-rise Building with High Damping Device”, *Earthquake Engineering and Structural Dynamics*, Vol.24, pp.655-671.

Sugano, T. et al. (1998), “Design of 45-Story Reinforced Concrete Building with High-strength Materials”, *Structural Engineers World Congress*, July, T205-2.